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TAMPERE UNIVERSITY OF TECHNOLOGY

JESSE BACKMAN
CONCEPT EVALUATION AND MODULARITY IN PRODUCT
DEVELOPMENT

Bachelor's thesis

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Tarkastaja ja aihe hyväksytty

ABSTRACT

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This bachelor's thesis intended to study concept evaluation and modularity in literature. The purpose of the literature review was to find different ways to evaluate product concepts, explore modularity and product development. The thesis was done in a Finnish company operating in the rock crushing industry as part of a preliminary study of a product development project. In addition to the literature review, the aim of the work was to produce a product development proposal for the company.

The literature review includes an overview of the overall product development process during which concepts are evaluated. An overview of the product development process was included in order to understand the context in which concepts are evaluated. Concept evaluation methods are focused on in more detail. Key concepts, benefits and drawbacks of modularity are introduced. Furthermore, the literature review introduces a design process for the development of a modular product family from existing products, which also takes into account the business environment of the company and how it interacts with the product development process.

The bachelor's thesis resulted in a product development proposal for rock crushing stations. In summary, the product development proposal was to develop a product family from rock crushing stations with configurable products that are to be included in the company's manufacturing and sales processes. An overview of the project, which resulted in the product development proposal, is presented. The project utilized the issues learned from literature and the tools found.

TIIVISTELMÄ

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Tämän kandidaatintyön tarkoituksena oli tutkia konseptien arviointia ja modulaarisuutta kirjallisuudessa. Kirjallisuusselvityksen tarkoituksena oli löytää erilaisia tapoja arvioida tuotekonsepteja, tutustua modulaarisuuteen sekä tuotekehitykseen. Työ tehtiin suomalaisen kivenmurskausalalla toimivaan yritykseen osana tuotekehitysprojektin esiselvitystä. Kirjallisuusselvityksen lisäksi työn tarkoituksena oli tuottaa kyseiseen yritykseen tuotekehitysehdotus.

Kirjallisuusselvitys sisältää katsauksen yleiseen tuotekehitysprosessiin, jonka aikana konsepteja arvioidaan. Katsaus tuotekehitysprosessista sisällytettiin, jotta ymmärretään konteksti jossa konsepteja arvioidaan. Konseptien arviointimenetelmiin syvennyttään työssä tarkemmin. Modulaarisuudesta esitellään keskeiset käsitteet sekä esitellään sen mahdollisia hyötyjä ja haittoja. Lisäksi kirjallisuusselvityksessä esitellään modulaarisen tuoteperheen kehittämiseen olemassaolevista tuotteista luotu suunnitteluprosessi, joka huomioi myös yrityksen liiketoimintaympäristön ja kuinka se ja tuotekehitysprosessi ovat vuorovaikutuksessa.

Kandidaatintyön tuloksena oli tuotekehitysehdotus kivenmurskausasemille. Tiivistettynä tuotekehitysehdotuksena oli kehittää kivenmurskausasemista tuoteperhe, jossa on konfiguroitavat tuotteet ja tuotteet sisällytetään yrityksen valmistus- ja myyntiprosesseihin. Projekti, jonka tuloksena tuotekehitysehdotus syntyi, esitellään pintapuolisesti. Projektissa käytettiin kirjallisuudesta opittuja asioita sekä löydettyjä työkaluja.

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LYHENTEET JA MERKINNÄT

CSL	Company Strategic Landscape
BfP	Brownfield Process
ETO	Engineered-to-order
MCDM	Multi-criteria decision-making
NIS	Negative ideal solution
PDS	Product Design Specification
PIS	Positive ideal solution
PSBP	Product Structure Blue Print
R&D	Research & Development
VCM	Value creation mechanism
VIKOR	<i>Vlsekriterijumska Optimizacija I Kompromisno Resenje</i> (multi-criteria optimization and compromise solution)

1. INTRODUCTION

Product development is a central theme in business today. New products and machines are developed to gain a competitive advantage by answering to changing market needs (Chen et al. 2014). Engineers have designed machines for a long time, and while companies and engineers often have their own ways of working, a generic engineering design process has developed over time. The generic way of developing products achieves the best result fastest, cheapest, more competently and completely, and with controlled processes the products are in the market faster (Mynott & Institution of Engineering and Technology 2012). The product development process is often described as a linear step-by-step process, but iteration is present inherently as development stages are often revisited.

One of the early phases of the product development process is concept creation, during which multiple concepts and solution variations are often developed. Existing designs and technical solutions can be utilized in the concept creation. To be able to select the best concept for further development, it is important to understand the weaknesses and strengths of each concept from multiple angles, for example from technical, financial and strategical points of view. Concept selection is a critical part of product development process, and systematic methods are more efficient than subjective and emotional choices. Systematic concept selection results in a customer-driven and competitive concept if selection criteria are derived from customer needs and current competition's existing products. (Ulrich & Eppinger 2012)

Customer needs and thus requirements for a product can often vary which introduces a challenge for product developers: how to design a product that can fulfil varying customer needs? One of modern design strategies utilized in product development to tackle the challenge is modularisation. Modularisation is defined by Andreasen (2011) as follows:

Modularisation aims for creating variety from the customer's viewpoint, whilst at the same time showing commonality between module variants, and such structural properties, that it reduces the complexity in the company's operations. Modularisation includes designing of modules, modular architecture and harvesting of benefits in areas where the effects can be seen by creating optimal conditions for these areas.

Various benefits can be achieved with modularisation of products, such as reduced costs during product lifecycle and increased product variety (Hansen & Sun 2010), and many companies, such as Volkswagen, successfully utilize modularisation in their product

family design. The benefits are naturally highly desirable for any company with possibility for designing modular product families. However, in addition to benefits, modularisation also poses challenges to companies. In order to successfully design a modular product or a product family, five essential design elements should be considered: “partitioning logic (reasoning for the modular structure/product family), set of modules, interfaces, architecture and configuration knowledge” (Pakkanen 2015).

This Bachelor’s thesis includes a literature review and a business case. The main objective of the thesis is to find an answer from literature to the following two questions:

- **How to compare existing products or concepts and select the best solution?**
- **How to develop a modular product or product family from existing products?**

The business case is a pre-study for a product development project, which includes a comparison of existing product variety from a modular product development point of view. The business case is conducted in a company in the aggregates business. Answers found from literature to the aforementioned questions are utilized in the business case. The literature review is introduced first before business case and discussion.

The first chapter discusses the generic engineering process with an emphasis on concept selection. The entire engineering process is included to provide context for concept evaluation and to understand the different angles that are considered during concept evaluation. Multiple concept evaluation and selection methods from literature are introduced.

In the second chapter, theory of modularity is discussed. The chapter includes definitions of central themes in modularisation and an overview of The Brownfield Process (BfP), a comprehensive approach to developing a modular product family from existing products, by Pakkanen (2015).

In the third chapter, the business case is introduced. In the chapter the background of the project and some central tasks that resulted in a product development proposal are discussed. The product development proposal is also introduced briefly.

The fourth chapter includes a conclusion and discussion from the author. Overall, the project was successful and initial feedback in the company has been positive.

2. GENERIC ENGINEERING DESIGN PROCESS

In this chapter an overview of the generic engineering design process is made. Gericke & Blessing (2012) have analysed different design process models and identified six generic stages in the engineering design process:

1. Establishing a need
2. Analysis of task
3. Conceptual design
4. Embodiment design
5. Detailed design
6. Implementation

The generic contents of each phase are here derived from design process models by Ulrich & Eppinger (2012), Pahl et al. (2007) and Pugh (1991). Differences between the models are naturally present in terms of scope, contents and order of each stage, but generally similar topics can be identified in all three methods. An emphasis is placed on identifying where in the process and how design concepts can be evaluated, and three different evaluation methods for design concepts are discussed. An overview of the generic engineering design process and how the stages of the selected models relate to it is presented in Table 1.

Table 1. *Engineering design models. Table after Gericke & Blessing (2012).*

Model	Establishing a need	Analysis of task	Conceptual design	Embodiment design	Detailed design	Implementation	
Ulrich & Eppinger (2012)	Planning		Concept Development	System-Level Design	Detail Design	Testing and Refinement	Production Ramp-Up
Pahl et al. (2007)	Task	Clarification of task	Conceptual design	Embodiment design	Detailed design	X	
Pugh (1997)	Market	Specification	Concept design		Detail design	Manufacture	Sell

2.1 Establishing a need

During the first phase of the engineering design process, a need for product development is established in all three selected design process models. The phase is referred to as “Planning” by Ulrich & Eppinger (2012), “Product Planning” by Pahl et al. (2007) and “Market” by Pugh (1991). Ulrich & Eppinger (2012) state that the phase is also often called “phase zero”, as it is done before launching a product development project. From the selected design processes, two main themes of the phase can be identified: identifying business opportunities and preliminary product planning.

Identifying business opportunities includes external and internal situation analysis. External situation analysis considers assessing current market situation and technology advancements and estimating future developments in both areas. Identifying needs for

product development and market trends are also taken into account. Internal situation analysis includes issues such as “*Assessing the Company’s Own Competence*” (Pahl et al. 2007). The external and internal analysis are not to be done in isolation, but in respect to each other. The aim is to identify an opportunity or a need in the market that lines up with the company’s competence, aims and overall strategy.

During preliminary product planning, an initial product proposal that includes some product requirements is defined. The requirements for a product can be for example intended product functions, financial requirements or time restrictions. The selected design process models mention these issues with varying emphasis.

2.2 Analysis of task

The need for a product established in the first phase of the design process should then be analysed in more detail. It is often the case that the need for a new product in a company arises outside the product development team, for example from customer feedback or a sales person losing business opportunities to a competitor’s new solution. The initial need often considers unmeasurable elements, that should be described as quantitatively as possible. Pahl et al. (2007) suggest using three questions to formulate a requirements list:

- “What are the objectives that the intended solution is expected to satisfy?”
- “What properties must it have?”
- “What properties must it not have?”

The requirements should form a “design boundary” (Pugh 1991) that considers a wide range of issues from performance, maintenance and product attribute requirements to target product cost and delivery requirements. Pahl et al. (2007) suggest that the listed requirements should be divided to demands, which need to be present in the final solution, and wishes which should be considered where possible. Ulrich & Eppinger (2012) similarly propose that customer needs should be divided to primary and secondary needs and then ranked hierarchically in terms of their importance.

Various tools and checklists are introduced for forming the requirements list in the literature. The result of the second phase is a list of requirements in all the selected methods, albeit named differently: “Product Design Specification (PDS)” (Pugh 1991), “Requirements list” (Pahl et al. 2007), “Customer needs list” (Ulrich & Eppinger 2012).

2.3 Conceptual design

During the conceptual design phase concepts matching the listed requirements will be created and evaluated. Based on the evaluation, concepts are eliminated, refined or selected for further development. A conceptual design describes approximately the

technology, working principles and form of the product, and how the product will fulfil the requirements (Ulrich & Eppinger 2012).

The process of conceptual design can be simplified to three stages:

- identifying key problems and functions
- creating concepts based on existing solutions and new ideas
- evaluating the concepts and concept selection

These stages are identified in the conceptual design methods displayed in Figure 1 and Figure 2.

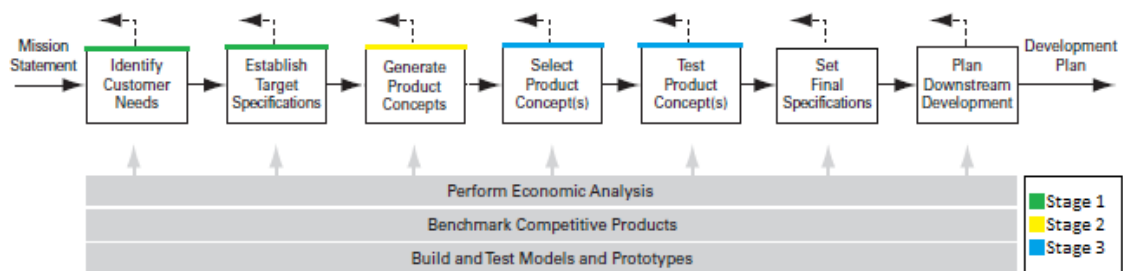


Figure 1. *Conceptual design phase. Modified from Ulrich & Eppinger (2012).*

The identification of key problems is done from the requirements list. Key problems have a direct bearing on the intended function and essential constraints, are qualitative and formulated in a solution-neutral way (Pahl et al. 2007). For creating a concept, it is suggested to consider both existing working structures and new ideas.

It is recommended that concepts are created by individuals, as working in groups may limit creativity and quantity of ideas. However, groups perform better in concept evaluation and development. (McGrath 1984)

Three different methods for evaluation of design concepts are introduced in more detail to find an answer for RQ1. The selected methods – a step-by-step evaluation process from Pahl et al. (2007), Rough sets & VIKOR -method (Tiwari et al. 2015) and decision matrices – are selected on the basis that they introduce different ways of concept evaluation.

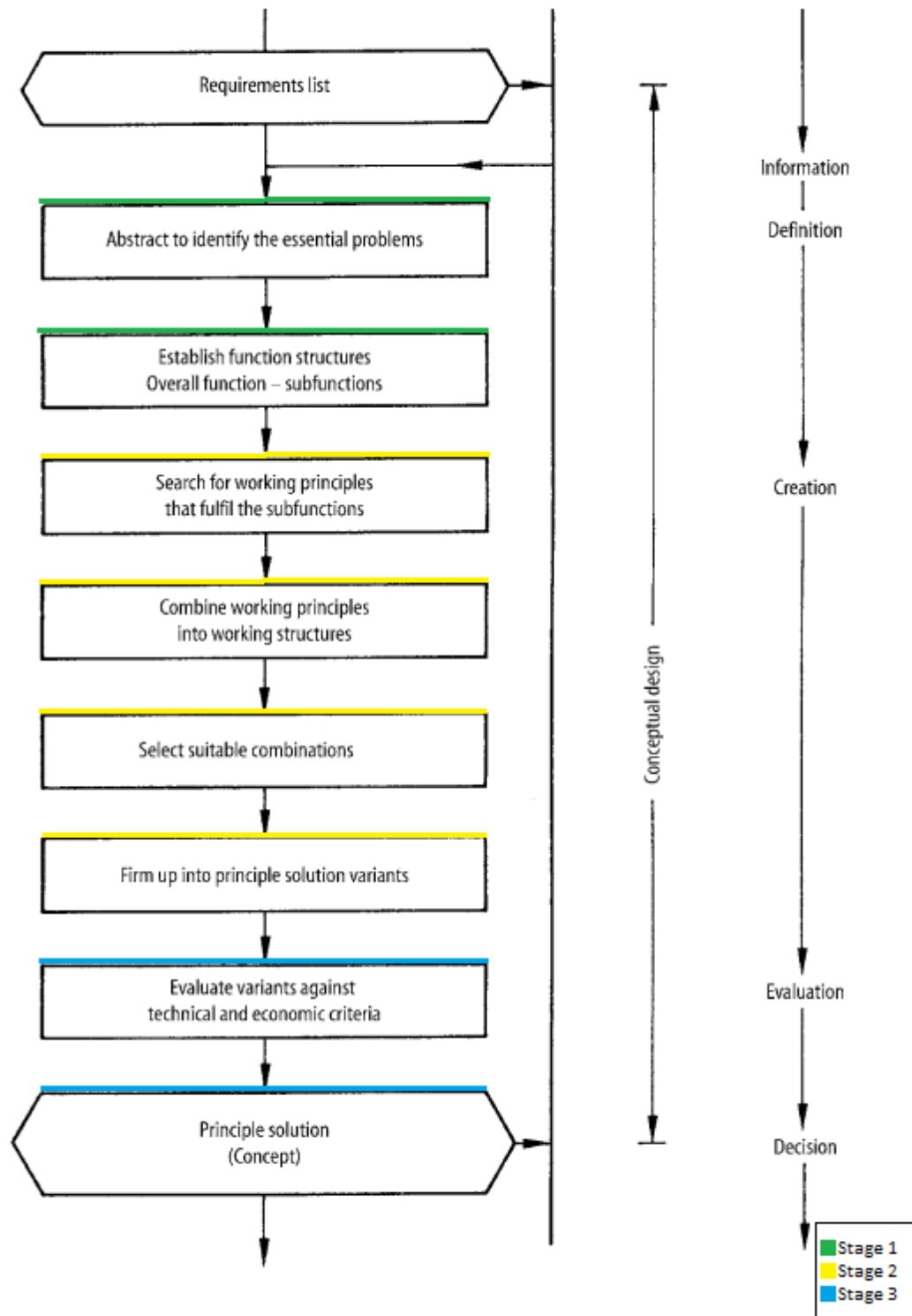


Figure 2. Conceptual design steps. Modified from Pahl et al. (2007).

2.3.1 Step-by-step concept evaluation

Pahl et al. (2007) introduces a step-by-step evaluation process based on Cost-Benefit Analysis based on the systems approach (Zangemeister 1970) and Guideline VDI 2225 (VDI 1997). The eight steps in the introduced evaluation process are: *Identifying Evaluation Criteria*, *Weighting Evaluation Criteria*, *Compiling Parameters*, *Assessing Values*, *Determining Overall Value*, *Comparing Concept Variants*, *Estimating Evaluation Uncertainties* and *Searching for Weak Spots*.

During the first step, *Identifying Evaluation Criteria*, a set of key objectives of the solution is determined. From these objectives the evaluation criteria can be formed. The objectives are usually based on a requirement list and general constraints of the solution, and they often include multiple factors of varying importance. A good set of objectives takes all relevant requirements and constraints into account. Individual objectives should be independent so that there is no relation between objectives. Lack of relativity in this instance means that an objective's score should not influence another objective's score. Additionally, the properties that are to be gauged should ideally be measurable, but if that is not possible then at least describable in verbal terms. (Pahl et al. 2007)

When evaluation criteria are derived from the previously defined objectives, all criteria should be formulated in a way that when scored, a higher score indicates better. For this step, Cost-Benefit Analysis provides a tool for organizing the objectives in a way that helps determine relations between and importance of individual objectives. The objectives are arranged in an objectives tree. On the horizontal axis there are different objective areas and on the vertical axis the level of complexity. It is then a simple process to pick out the evaluation criteria from the lowest level of complexity. An example of an objectives tree is shown in Figure 3. (Pahl et al. 2007)

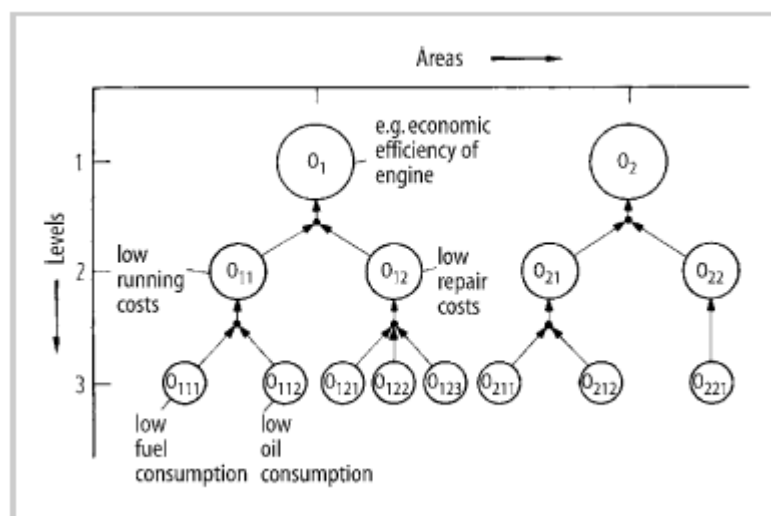


Figure 3. Structure of an objectives tree (Pahl et al. 2007).

Before evaluation criteria can be settled, their relative value or importance to the solution must be determined. This is done in the second step, *Weighting Evaluation Criteria*, and the objectives tree established in the previous step is useful for this stage. Weighting is done in order to better understand what is important for the overall value of the solution and also to exclude any insignificant criteria. In Cost-Benefit Analysis, each individual evaluation criterion is given a weighting factor, that is a real, positive number between 0 and 1. (Pahl et al. 2007)

Weighting factors are not given arbitrarily, but in respect to the previous, higher level of complexity. For example, in Figure 3, the objectives O_{11} and O_{12} are weighted in relation to the previous level, O_1 . This type of step-by-step weighting is likely to produce a reasonable ranking, as it is simpler to weight sub-objectives in relation to their parent objective one level above rather than weighting each objective in relation to the highest level of complexity. (Pahl et al. 2007)

The sum of weighting factors in relation to the previous level of complexity, in this case O_{11} and O_{12} , must be 1. Similarly, O_{111} and O_{112} are weighted in relation to O_{11} so that their sum is 1. The weight of an objective in relation to the highest level, in this case O_1 , can be calculated by multiplying the weighting factors along the path from O_1 to the objective in question. For instance, if O_{11} has a weighting factor of 0.25 in relation to O_1 and O_{111} has a weighting factor of 0.45 in relation to O_{11} , the weighting factor of O_{111} in relation to O_1 is $0.25 * 0.45 = 0.1125$. (Pahl et al. 2007)

After determining the evaluation criteria and their relative importance to the solution, parameters are assigned to the selected criteria in the third step, *Compiling Parameters*. These objective parameters, as they are called in the Cost-Benefit Analysis, should be quantifiable or in the least be expressed by as concrete statements as possible. For example, an evaluation criterion for combustion engine could be “Low fuel consumption” and a quantifiable parameter “Fuel consumption g/kWh”. An example of a concrete statement could be “Simplicity of components” as a parameter of the evaluation criterion “Simple production”. (Pahl et al. 2007)

The fourth step is the actual evaluation of the variants, *Assessing Values*. In this phase, the different solution variants are given points. Cost-Benefit Analysis suggests a range from 0 to 10 and the Guideline VDI 2225 employs a point range from 0 to 4. The narrower range is generally more useful when rough evaluations are sufficient, as in cases where the characteristics of the variants are not well-known. It is suggested to start the evaluation by identifying any extreme characteristics, as in the very good or deficient, and assigning the corresponding points (0 and 4 or 10) to them. After assigning the extremes, it is easier to find suitable points for the rest of the characteristics. These points are to be multiplied by the corresponding weighting factors of the evaluation criteria in order to find benefit values, as the Cost-Benefit Analysis calls them. (Pahl et al. 2007)

Determining the correlation between parameter magnitude and value-scale before assigning points can be useful, as verified correlations such as safe decibel levels are uncommon. However, these self-determined correlations can be influenced by subjective influences, which should be considered. (Pahl et al. 2007)

The fifth step, *Determining Overall Value*, is where the overall value of each solution variant is calculated. The overall value OV of variant j is calculated as

$$OV_j = \sum_{i=1}^n v_{ij}, \quad (1)$$

where n is the amount of evaluation criteria and v_{ij} is the value of, or points assigned to, i^{th} evaluation criterion for the variant j . The overall weighted value OWV of variant j is calculated similarly as follows:

$$OWV_j = \sum_{i=1}^n wv_{ij}, \quad (2)$$

where wv_i is the i^{th} weighted value or benefit value. (Pahl et al. 2007)

For the sixth step, *Comparing Concept Variants*, several ways of comparison are proposed. A simple comparison of the maximum overall values results to a relative comparison of the variants. A rating can be formed by comparing the overall value of a variant to an imaginary ideal value, which has the maximum possible points or value. If cost estimates are possible, it is suggested to determine technical and economic rating separately. Technical rating would be calculated in reference to an ideal technical solution and economic rating in reference to comparative costs. When these two ratings are calculated separately, deriving the overall value can be challenging. For this purpose, a strength diagram or numerical methods are proposed. A strength diagram or *s-diagram* is suggested by VDI 2225 and an example is show in Figure 4. Numerical methods of simple arithmetic mean or a hyperbolic method can be used for calculating a numerical value for overall rating. Solution variants can also be roughly compared with, for example, a binary evaluation matrix. (Pahl et al. 2007)

In the eighth step, *Estimating Evaluation Uncertainties*, possible subjective errors and procedure-inherent shortcomings are attempted to be identified. Subjective errors are commonly errors such as introducing bias and partiality to the evaluation, inadequate evaluation criteria not suitable to all solution variants, evaluation of variants in isolation, interdependence or incompleteness of evaluation criteria or unsuitable value functions. Procedure-inherent shortcomings often arise from erroneous predicted parameter magnitudes and values. (Pahl et al. 2007)

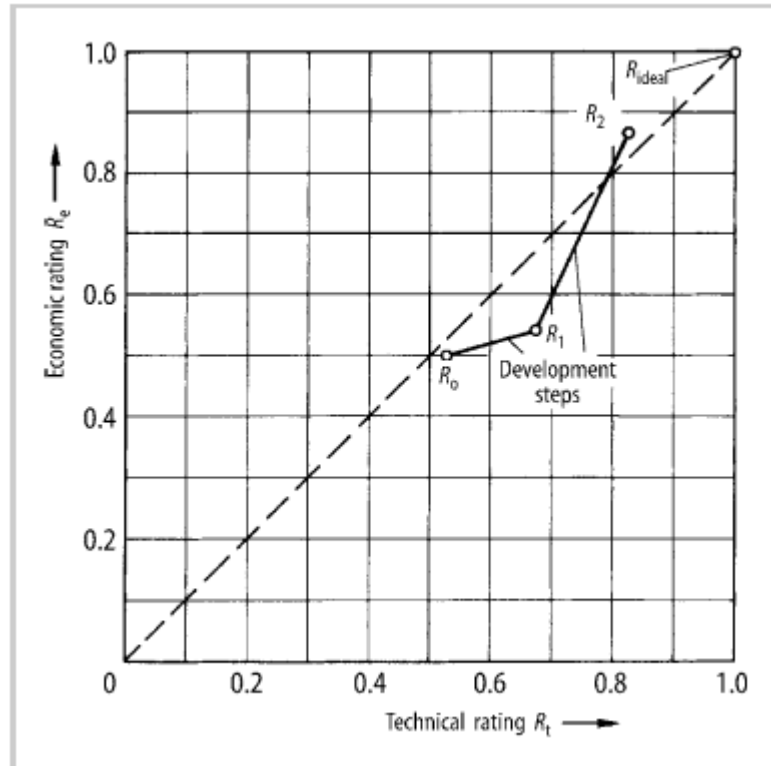


Figure 4. An example of a s-diagram (Pahl et al. 2007).

Finally, *Searching for Weak Spots* of the solution variants is a straightforward procedure of identifying below average values for evaluation criteria. It is important to identify weak spots specifically in solutions with high overall scores, as serious weak spots can make a solution variant unfit. Thus, a solution variant with balanced score profile is likely to be better than a solution with both high and low scores even when both solutions have similar overall score. (Pahl et al. 2007)

2.3.2 Rough sets & VIKOR -method

Tiwari et al. (2015) introduce a concept evaluation method that utilizes calculations to identify best concept that fulfils the design criteria. The reasoning for using a numerical analysis to solve a complex multi-criteria decision-making (MCDM) problem is that non-numerical approaches are not as accurate and efficient. The modified rough *Vlsekriterijumska Optimizacija I Kompromisno Resenje* (VIKOR) (multi-criteria optimization and compromise solution) was developed to reduce subjectivity in the concept evaluation process. (Tiwari et al. 2015)

The method is divided in two phases. In the first phase, the design criteria are ranked relative to each other and given initial weights. The design criteria are assigned importance values, which are used to compute the relative importance rating of each design criterion with rough set enhanced fuzzy approach introduced by Zhai et al. (2008). In the second phase, customer's preference of design attributes in the form of rough

numbers is introduced alongside the relative importance ratings and rankings in extended VIKOR method with interval numbers, proposed by Sayadi et al. (2009). The result of the phase is a ranking of concept variants. (Tiwari et al. 2015)

The first phase can be expressed in four basic steps. First, design attributes and design alternatives are suggested to be generated by designers and experts working on the project. Design attributes are based on customer requirements. Design alternatives are different combinations of attribute values for design attributes. For example, a design alternative can have design attribute values of “Maintenance need: high” and “Capacity: medium”. Second, design attributes are assigned importance by multiple designers. It is suggested to use a 9-point scale, displayed in Table 2. (Tiwari et al. 2015)

Table 2. 9-point scale for assigning importance to design attributes
(Tiwari et al. 2015).

Scale for measuring relative importance of design attributes.

Scale (importance)	Crisp value and STFN
Very low (VL)	1 [0, 2]
Very low	2 [1, 3]
Low (L)	3 [2, 4]
Low	4 [3, 5]
Moderate (M)	5 [4, 6]
Moderate	6 [5, 7]
High (H)	7 [6, 8]
High	8 [7, 9]
Very high (VH)	9 [8, 10]

These importance values are then computed to rough numbers. Rough numbers are based on rough set theory (Pawlak 1982), which can be utilized for taking advantage of inherent information in data in analysis. Approximation operators are used to deal with vagueness and uncertainty. (Tiwari et al. 2015) For the computation equations and rough number theory, see Tiwari et al. (2015). An example of the assigned importance values and their corresponding rough numbers are displayed in Table 3 and Table 4.

Table 3. Example of assigned importance values to design attributes. Modified from Tiwari et al. (2015).

Importance assigned to design attributes by team of designers.

Design attributes DA_i	Designers			
	D_1	D_2	D_3	D_4
Expected mechanical safety	H (7) [6, 8]	M (5) [4, 6]	H (7) [6, 8]	L (3) [2, 4]
Amount of wear	M (5) [4, 6]	M (5) [4, 6]	H (7) [6, 8]	H (7) [6, 8]
Operating and maintenance cost	H (7) [6, 8]	L (3) [2, 4]	L (3) [2, 4]	H (7) [6, 8]
Overload reserve of a machine	L (3) [2, 4]	L (3) [2, 4]	L (3) [2, 4]	M (5) [4, 6]

Table 4. Example of computed rough numbers for design attributes' importance values (Tiwari et al. 2015).

Importance assigned to design attributes in the form of rough numbers.

Design attributes DA_i	Designers			
	D_1	D_2	D_3	D_4
Expected mechanical safety	[5.5, 7]	[4, 6.33]	[5.5, 7]	[3, 5.55]
Amount of wear	[5, 6]	[5, 6]	[6, 7]	[6, 7]
Operating and maintenance cost	[5, 7]	[3, 5]	[3, 5]	[5, 7]
Overload Reserve of a machine	[3, 3.5]	[3, 3.5]	[3, 3.5]	[3.5, 5]

As the last step in the first phase, the rough number importance ratings are normalized and a relative importance ranking of design attributes is formed. The attributes are ranked as the “most important, important, medium important [sic] and low important [sic] design attribute” (Tiwari et al. 2015), as proposed by Zhai et al. (2008). The main steps of the first phase are displayed in Figure 5.

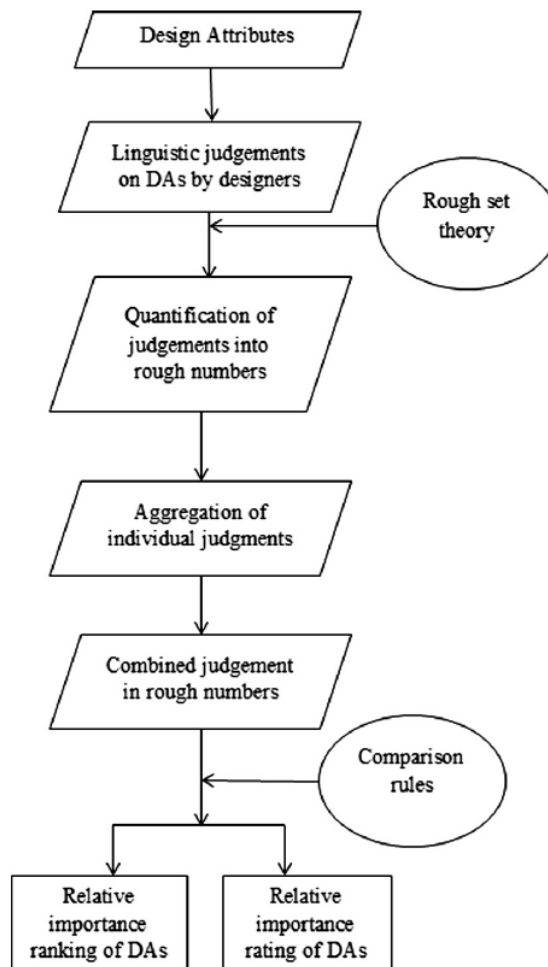


Figure 5. First phase of the modified rough VIKOR-method (Tiwari et al. 2015).

During the second phase, evaluation model between the design alternatives is developed. Overview of the second phase of the method is displayed in Figure 6. The second phase can also be presented in four basic steps. First, customer preference on design attribute values are gathered. It is suggested to gather preference from multiple customers. The preferences can be assigned values such as “7 = high preference; 5 = medium preference; 3 = low preference; 1 = very low preference”. The results are combined and from the combined results a rough group preference matrix is computed. Customer’s perceptions variety for each design attribute value can be observed from the matrix. (Tiwari et al. 2015)

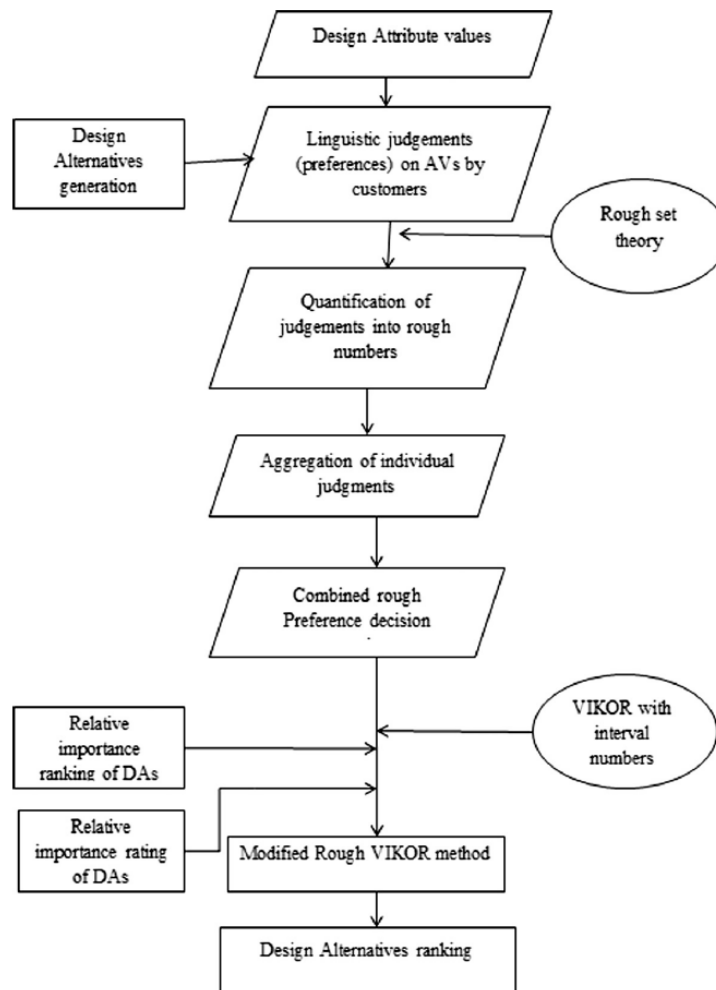


Figure 6. Second phase of the modified rough VIKOR-method (Tiwari et al. 2015).

Next, Positive ideal solution (PIS) and Negative ideal solution (NIS) are identified from the rough group preference matrix. PIS and NIS are based on the relative importance of design attributes. For most important and important design attributes, the PIS is the largest upper limit and NIS the smallest lower limit of the rough numbers related to the design attribute. For medium importance design attributes, PIS and NIS are the average of upper and lower limits respectively. For low medium importance design attributes, the smallest upper limit is the PIS and the largest lower limit is the NIS. (Tiwari et al. 2015)

Last, the aggregating function interval for each design alternative is computed with the NIS and PIS values and solutions are ranked. The optimism level of decision maker can also be accounted for in the calculations. From the design alternative ranking, best solution can then be selected. (Tiwari et al. 2015)

2.3.3 Decision matrices

Decision matrices can be used for comparing concepts in relation to each other with specified selection criteria. These matrices are often used for “concept screening” (Ulrich & Eppinger, 2012) in the early stages of concept evaluation. Pugh (1991) introduces an evaluation matrix, which has been the basis for many concept selection methods developed since, for example Ulrich & Eppinger (2012).

The process for creating an evaluation matrix as described by Pugh (1991) is straightforward. Pugh (1991) introduces some prerequisites for the concepts to be evaluated: concepts should be trying to provide a solution to the same problem and they should be depicted on the same level of detail. The concepts are placed as the columns and evaluation criteria as the rows of the matrix. The selected decision criteria should be unambiguous and based on the requirements of the product. On the matrix, a sketch or other visual representation of each concept should be present.

Before evaluation, a datum to which all concepts are compared to should be selected. If previous solutions do not exist, it is suggested to use the concept that is intuitively the best in the decision group’s opinion. All concepts are then compared to the datum and +, - or S are placed on the matrix cells. A ‘+’ is placed when the concept is ‘better’ than the datum in relation to a criterion. A ‘-’ is placed when the concept is ‘worse’ and ‘S’ is placed when it is difficult to decide if a concept is better or worse than the datum. (Pugh 1991) An example of an evaluation matrix is shown below.

	Concepts						
Selection Criteria	A Master Cylinder	B Rubber Brake	C Ratchet	D (Reference) Plunge Stop	E Swash Ring	F Lever Set	G Dial Screw
Ease of handling	0	0	-	0	0	-	-
Ease of use	0	-	-	0	0	+	0
Readability of settings	0	0	+	0	+	0	+
Dose metering accuracy	0	0	0	0	-	0	0
Durability	0	0	0	0	0	+	0
Ease of manufacture	+	-	-	0	0	-	0
Portability	+	+	0	0	+	0	0
Sum +’s	2	1	1	0	2	2	1
Sum 0’s	5	4	3	7	4	3	5
Sum -’s	0	2	3	0	1	2	1
Net Score	2	-1	-2	0	1	0	0
Rank	1	6	7	3	2	3	3
Continue?	Yes	No	No	Combine	Yes	Combine	Revise

Figure 7. An example of an evaluation matrix with scored concepts. Instead of ‘S’, zeroes are used. (Ulrich & Eppinger, 2012).

The sum of +’s, -’s and S’s are calculated and placed on the matrix. These values can be used for evaluating the initial strength or weakness of the concept. Based on the values and evaluation, concepts can be selected for further development or disregarded. It is suggested to pay attention to the weaknesses of the selected concepts and look for ways to improve the concept. Modified concepts should be placed on the matrix as a new entry and weak concepts that cannot be improved should be removed from the matrix. By repeating these steps, the strongest concepts will remain in the matrix. (Pugh 1991)

The matrix is here displayed as a tidy table, but in reality these matrices are often “messy collages of drawings and notes” (Frey et al. 2009). This reflects the stage during which the matrix is often used – early concept development. As a rather simple tool, the evaluation matrix seems to be suitable for a coarse elimination of concepts or collection of information, but for more comprehensive evaluation, other methods could prove to be more effective.

Vanhatalo et al. (2010) introduce a concept evaluation matrix tool that presents the concept’s behaviour in a business environment (see Figure 8). The tool aims to help with identifying situations where unsuitable concepts could otherwise be developed further. For example, a concept could be easily manufactured, but it would not suit the company’s business environment or production network.

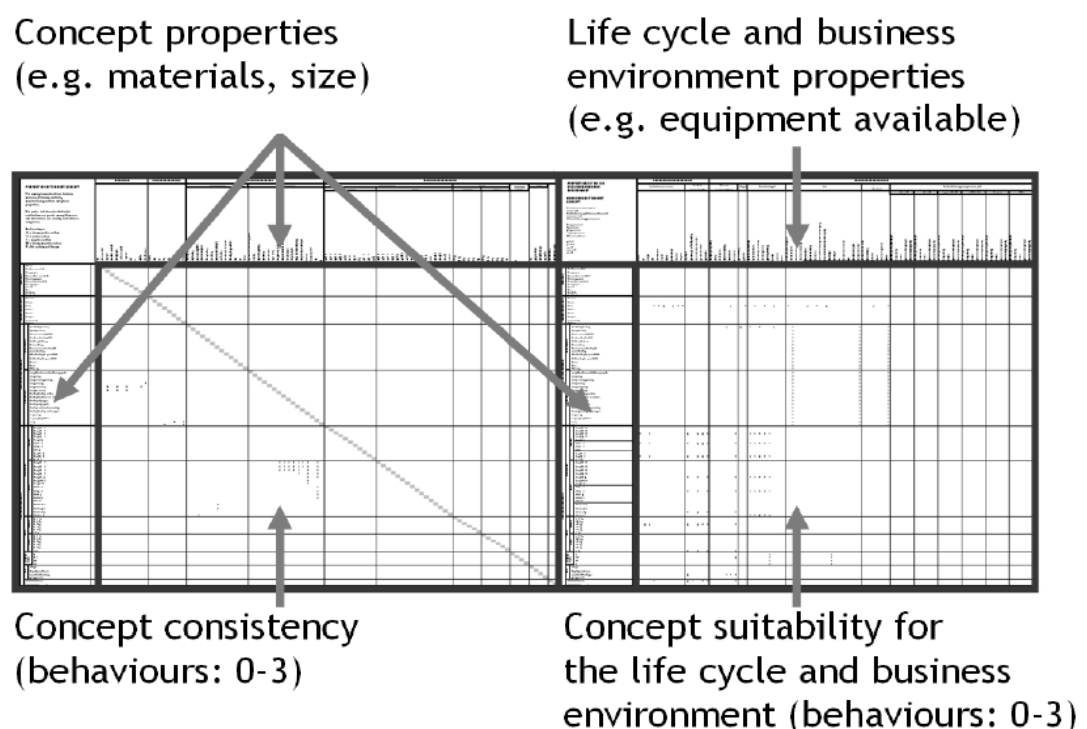


Figure 8. *Layout of a concept evaluation tool (Vanhatalo et al. 2010).*

The tool is suggested to be used in four phases: in the first two phases, the properties of the concept and the properties of the life cycle and business environment are clarified. Properties are to be listed before the actual evaluation process. In the third and fourth phase, consistency of the concept and suitability of the concept for the life cycle and business environment are evaluated. (Vanhatalo et al. 2010)

In the first phase the properties of the concept are identified. These properties can be divided to groups, for example in the boat industry the property groups could be materials, manufacturing methods, fastening methods and physical properties. Materials group could include steel, composites, wood and rubber. Parts made of same material can be manufactured in different ways, which should also be identified. There are various ways of fastening the parts together, such as welding or screw fixation. Measurements, weight and number of parts are examples of physical properties. (Vanhatalo et al. 2010)

In the second phase the properties are divided to properties linked with value chains and properties linked with processes and services. The division is based on the CSL framework model by Juuti et al. (2007). For example, waterproofness of a boat window is linked with the value chain as windows are sealed during manufacturing. The aim of the phase is to find “the best compatible product structure / delivery process pairs that support the chosen objectives.” (Vanhatalo et al. 2010)

The third phase aims to ensure that the concept does not have any internal conflicts and could theoretically be turned into a product. Properties are compared to each other to find out behaviour between them, and the behaviour is marked to the matrix according to the notation in Table 5. (Vanhatalo et al. 2010)

Table 5. *Notation for describing behaviour between properties (Vanhatalo et al. 2010)*

Evaluation scale	Description of behaviour
3	Strong positive
2	Positive
1	Negative
0	Strong negative
?	Behaviour unknown

Strong positive means that the properties are an ideal match, for example welding a steel pipe. Strong negative can be interpreted as “impossible”. Positive and negative behaviours are could be “doable, but not ideal” and “doable, but very challenging” respectively. Not all property-pairs must be analysed, as behaviour is not always present. In these cases, the relative cells are greyed out. (Vanhatalo et al. 2010)

In the fourth phase, concept properties are estimated in relation to the life cycle and business environment properties of the company. The behaviours between the properties are marked in the same way as in the previous phase. The result is a view of how well the

concept fits the network and value chain of the company. For example, it might become apparent that with the current subcontractors manufacturing of a concept is not possible. Then an evaluation could be made whether to make changes to the concept or the value chain. (Vanhatalo et al. 2010)

The tool introduces the business environment to the concept evaluation process, which is naturally important to a company. Analysing concepts only from a technical point of view without considering the life-cycle and business environment could pose some problems later in the product development process. The matrix is a valuable tool for quick concept evaluation.

2.4 Embodiment design

After conceptual design, an embodiment design phase is to be completed. During embodiment design, general arrangement and spatial compatibilities, preliminary form designs and production processes are determined. Embodiment design phase results in a layout of the product, which considers product architecture, sub-systems and interfaces, production and assembly scheme. It is important to continuously evaluate the design with technical and economic criteria during the phase. (Pahl et al. 2007, Ulrich & Eppinger 2012)

During embodiment design phase it is important to realise that changes and alterations in one area are likely to have an effect in other areas. The complexity of the phase should be considered and the needed time taken to ensure a high-quality design. Information and input from various functions of the company is required in the phase, which is likely to require a considerable effort. For example, input from production, procurement, financial management and service functions is likely needed.

2.5 Detailed design

During the detailed design phase, the details of the product, or specification, are determined. The details include drawings, materials, surface properties of parts, dimensions and production documents. During the detailed design phase, it is important to pay attention to details and double-check all documents. Pahl et al. (2007) states that often the preceding steps of engineering design process must be repeated and corrections to the detailed design are made to improve assemblies and components. Thus, when the step is done with great attention to detail, future work is also made easier.

2.6 Implementation

The implementation of the products can be done when detailed design is completed. Implementation often includes building prototypes of the products that are to be tested in their intended applications. Prototypes are tested to find out if the product works as

intended and if it satisfies customer needs (Ulrich & Eppinger 2012). The first prototypes are often not built in the actual processes that will be used in production as to not interfere with them. After extensive tests and acceptance of the prototype, the production is moved to the intended production system.

In addition to production of prototypes and testing, implementation of new products includes both internal and external product launch. Internal launch can include informing and training sales and support functions and launching an internal marketing campaign. External product launch is often a marketing campaign that aims to introduce the new product or product family to the market.

2.7 Key findings

In the chapter an overview of generic engineering process was made based on three design process models from literature. An emphasis was placed on concept evaluation methods and understanding the context where concepts are evaluated, and what is considered and why. The overview of generic engineering process provided the frame of reference in which concepts are evaluated. Concept evaluation methods were selected from the design process models and from other sources. It was found that concept evaluation is done to understand how well a concept fulfils both internal and external requirements. The methods can be qualitative, quantitative or a mix of both. Matrices are often used for visualising and lessening the complexity of the evaluation process. Concept evaluation is often an iterative process, where concepts are revised, combined and improved after being evaluated to produce the best possible solution.

3. THEORY OF MODULARITY

In this chapter, central concepts and themes of modularity alongside benefits from modularity are introduced from literature. A comprehensive design support for modularisation of a company's existing product variety, The Brownfield Process (BfP) by Pakkanen (2015), is also introduced.

3.1 Modularisation

Standard products are a common concept in the industry – they are products that have the same properties and behaviour from unit to unit. Often standard products are mass produced and require minimal amount or no engineering.

Modularisation and standardisation are occasionally mixed up in the industry, but there is a distinctive difference. Standardisation is what enables modularisation (Lehtonen 2007, according to Juuti 2008). Standardisation is a design tactic used to decrease variation of a property or behaviour in a technical system. Standardisation is not only done on design department or company level, but on many different levels, for example on the industry level in the form of ISO standards. (Juuti 2008)

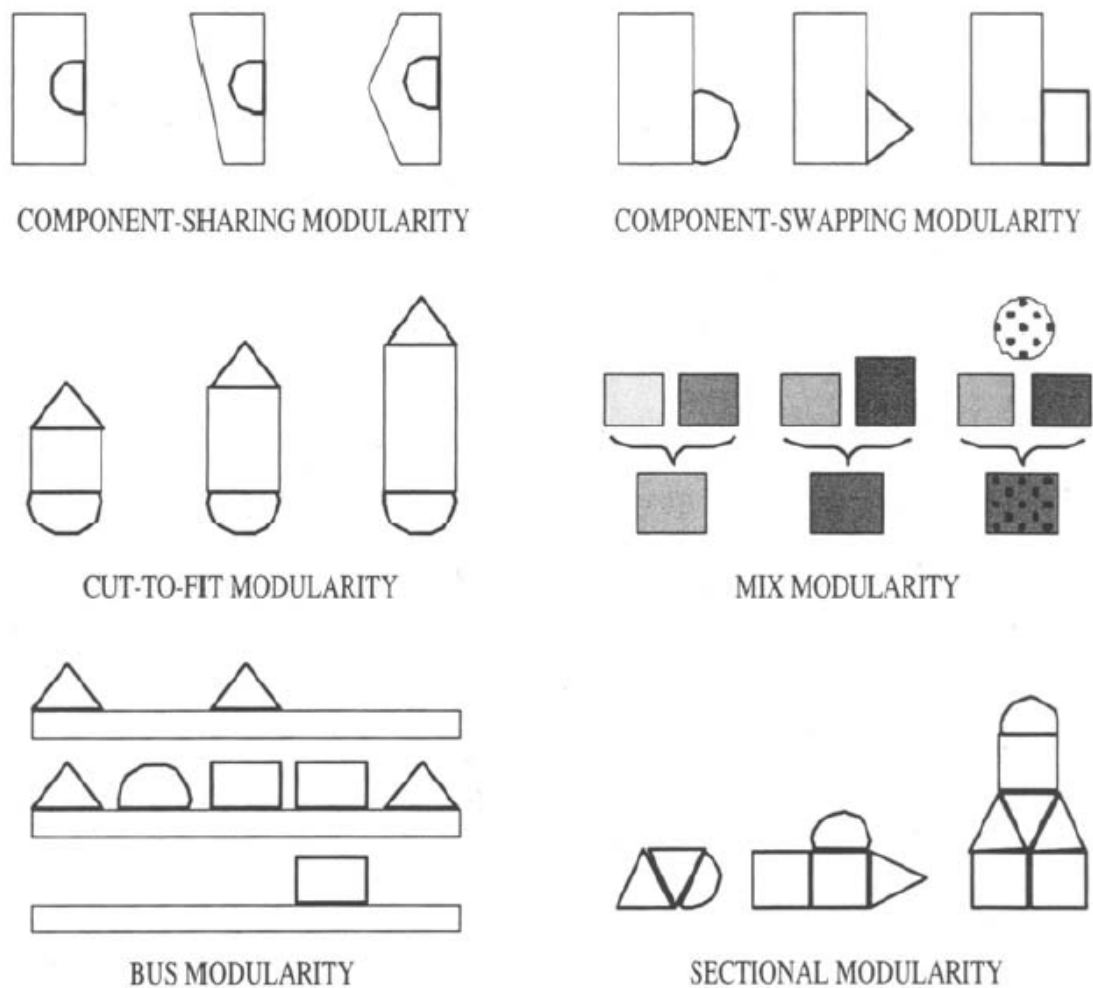
A modular system has been first described by Karl-Heinz Borowski in 1961 (Borowski 1961). Borowski (1961) establishes rules of a constructional element system (*Baukastensystem*). A *Baukastensystem* is defined as a system that consists of constructional elements (*Baustein*) of different size ranges (*Rangstufe*) in a selected solution level (*Auflösungsgrad*). Constructional elements are undivided entities within the system and thus have continuous interfaces in some sense, such as physical. In other words, a constructional element system consists of standardised constructional elements, that can be combined to assemble a limited or an unlimited number of different products in accordance to a construction plan (*Baumusterplan*). Borowski (1961) defines 9 different meta models for Baukasten systems, which are displayed in Figure 10. (Lehtonen 2007, Juuti 2008)

Lehtonen (2007) uses Borowski's *Baukastensystem* as a starting point for the definition of modularity. However, the type-selection of Borowski's meta models is based on a two-level solution level, which is an arbitrary solution, and so types of interchangeability (Abernathy-Utterback-Ulrich, see Lehtonen 2007) are selected as the basic types of a modular system. These interchangeability types are presented in Figure 9. (Lehtonen 2007).

A module is defined by Lehtonen et al. (2003) as follows: “A block (any assembly of the product or part of the system) is a module if it has an assigned interface and it is a part of a modular system.”

and a **modular system** is defined by Lehtonen et al. (2003) as follows: “A modular system is a system consisting of blocks which involves the interchangeability of the blocks.”

These definitions are also known as m-modularity (Lehtonen et al. 2003).



Source: From “Patterns of Industrial Automation,” by William J. Abernathy and James M. Utterback. Reprinted with permission from Technology Review, copyright 1978.

Figure 9. Types of interchangeability. (Abernathy & Utterback 1978, according to Pine 1993, see Lehtonen 2007).

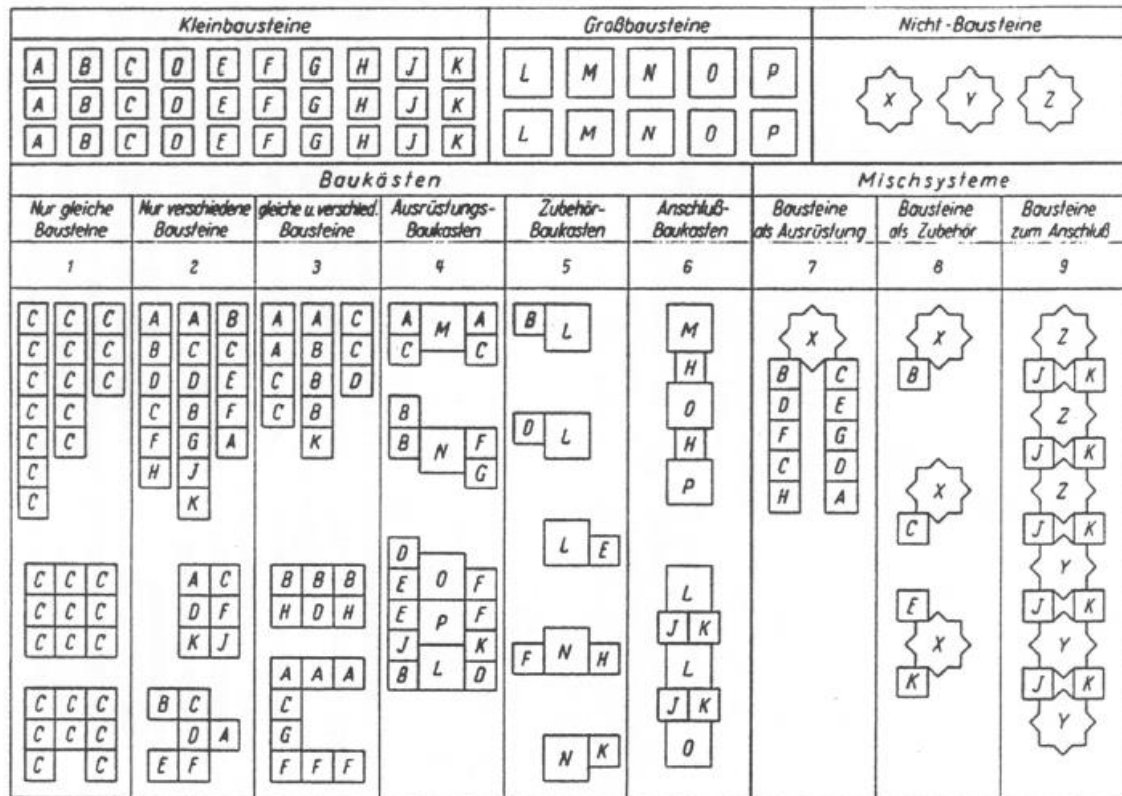


Figure 10. Meta models for Baukasten systems (Borowski 1961).

3.2 Module System

A modular system was defined as “a system consisting of blocks which involves the interchangeability of the blocks.” (Lehtonen et al. 2003) The elements of a module system based on Juuti (2008) are defined by Pakkanen et al. (2013) as follows:

- **Partitioning logic:** reasoning leading to a certain module division
- **Modules:** building blocks of the Module System
- **Interfaces:** enablers of interdependency and interchangeability of the modules
- **Architecture:** layout definition of the structure of Module System defining how modules and their interfaces are located in the product
- **Configuration knowledge:** compatibility and constraints of the modules and customer needs

Why these elements are related to modularisation and what information is included in each element?

Partitioning logic contains information of the reasoning behind module division of a product. It describes why a design is partitioned in a specific way (Pakkanen et al. 2016). The need for product variety stems from customer processes (Lehtonen et al. 2011) and

partitioning logic of a modular product should describe why there is a need for variety within the product. According to Juuti (2008), product elements are either standard, configurable, partly configurable or unique, and partitioning logic should provide the reasoning for the product element types. (Pakkanen et al. 2013) Product modularity increases the flexibility of configuration (Hansen & Sun 2010) and thus a need for product variety from customers is a strong driver for modularisation.

Modules or **a set of modules** contains information of the modules of a modular product. The included information can initially be for example a list of module candidates that is refined later in the development process into a list of definitive modules with detailed descriptions. (Pakkanen et al. 2013)

Interfaces between modules should be described in detail. Pakkanen et al. (2013) cite Stevens et al. (1998) who have determined an interface control document that includes information such as the requirements that the modules have for the interface (e.g. free space), mechanical properties or connections.

Architecture contains information about the modules, interactions and interfaces as stated by Andreasen (2011). Depending on the type of architecture – open or closed (Fujimoto 2007) – the information contained differs slightly. In a closed architecture all modules and combinations are defined, and in open architecture interfaces are defined but modules and combinations are not. (Pakkanen et al. 2013)

Configuration is defined by Mittal and Frayman (1989) as:

“Given: (A) a fixed, pre-defined set of components, where a component is described by a set of properties, ports for connecting it to other components, constraints at each port that describe the components that can be connected at that port, and other structural constraints (B) some description of the desired configuration; and (C) possibly some criteria for making optimal selections.

Build: One or more configurations that satisfy all the requirements, where a configuration is a set of components and a description of the connections between the components in the set, or, detect inconsistencies in the requirements.”

This definition applies to the configuration of a modular product. **Configuration knowledge** includes information required for configuration such as compatibilities of the modules, compatibilities of customer needs causing the need for variety and compatibilities between customer needs and modules (Pakkanen et al. 2013).

3.3 Benefits and challenges of modularisation

Hansen & Sun (2010) have studied 40 different modularisation cases in 22 different companies in the Nordic Europe. The study aimed to gain insight on how benefits of modularisation are perceived in the companies and if potential realised benefits match the perceptions. The study found that methodology and approaches for specifying benefits from modularisation are generally lacking and that perceived and realised benefits rarely match. A Modularization Benefit Matrix was developed for comparing the perceived and realised benefits, and while it was only tested in retrospect in the study, it is considered to be helpful in practical modularisation work. (Hansen & Sun 2010)

The mismatch between the perceived and realised benefits tells more about the lack of proper methodology and misconceptions about modularisation than it does about presence or absence of benefits in the author's opinion. If a product modularisation – or any other development – is done just for the sake of it without clarity in methodology and goals, it is likely that the efforts are wasted and results are difficult to gauge.

Hansen & Sun (2010) observed eight areas where benefits from modularisation were realised. It was observed that product modularity:

- reduces costs in the product life cycle due to the possibilities of economy of scale in production
- reduces delivery time due to the reduced possibilities of postponement in supply chain
- enhances speed in the product development process due to the possibilities for distribution of activities
- enhances speed in the product development process due to well-known structures in the product development project management
- enhances speed in the introduction of new product variants due to the reuse of components and structures
- enhances the variety due to the flexibility in the configuration of the final product
- enhances organizational flexibility due to the ease in communication of the product structure
- enhances organizational learning due to the inherent structure for accumulation of knowledge

These benefits were categorized to six major benefit driver categories and three major benefit categories. The six benefit drivers were further categorised under Research & Development (R&D) and Manufacturing & Logistics. R&D benefit drivers include: carry over, technical update and customization and styling. Manufacturing and Logistics drivers include: processes and organization, supplier availability and gradual completion.

The three observed benefit categories were: “cost, quality and complexity”, “capital binding” and “lead time reductions”. (Hansen & Sun 2010)

In addition to benefits, modularisation poses challenges to companies which might result in drawbacks. Pakkanen et al. (2018) have reviewed generic value creation mechanisms (VCM’s) “in the literature of product variety development based on modularisation - - “. Alongside benefits, these VCM’s introduce challenges that should be considered in product variety development. The figure below illustrates the VCM’s discussed in literature and key challenges are outlined after the figure.

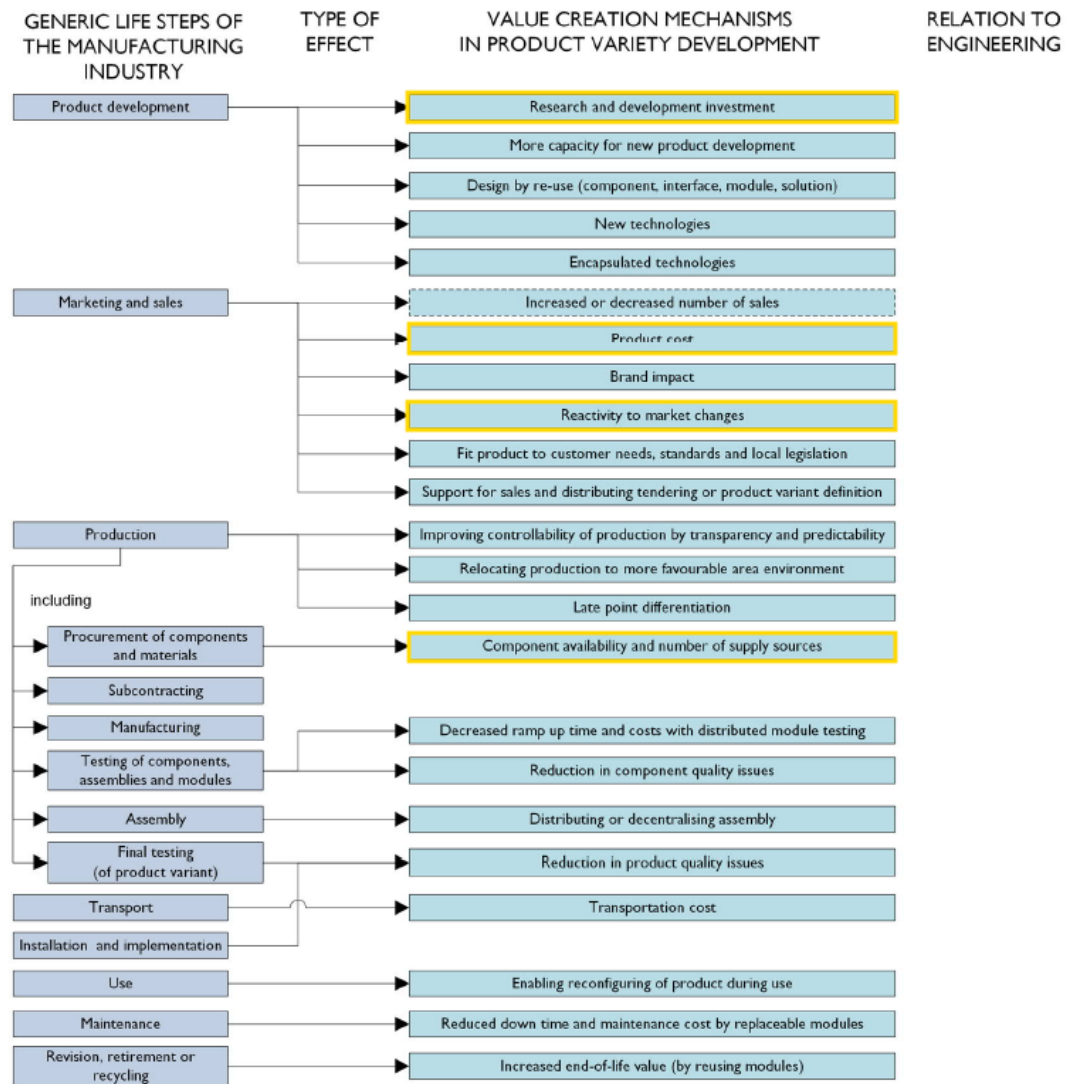


Figure 11. Value creation mechanisms of product variety development. Key VCM’s that pose challenges highlighted in yellow. Figure modified from Pakkanen et al. (2018).

From the VCM's identified by Pakkanen et al. (2018), four mechanisms that can cause drawbacks were identified: R&D investment, Product cost, Reactivity to market changes and Component availability & number of supply sources. The challenges that these VCM's introduce are listed below:

- **R&D investment:** According to Baldwin and Clark (2000), modular design requires investments due to additional work required in development, such as designing modules and testing.
- **Product cost:** Product variety can create additional costs in the product's life cycle if commonality is not considered (Andreasen et al. 1996).
- **Reactivity to market changes:** If the product or product family includes elements that are vulnerable to market changes, such as expectations, standards or legislation, and the vulnerabilities are not considered in design, the product's ability to react to changes in the market can decrease (Pakkanen et al 2018).
- **Component availability & number of supply sources:** If many supply sources are available, economical part procurement is possible, where competition between suppliers can be created and the total cost of production can be reduced. However, in the opposite case of only a few available supply sources, part prices can increase. This is the key reason why component availability & number of supply sources should be considered in product variety development. (Pakkanen et al 2018)

To conclude, modularisation can bring a wide range of benefits, but there are challenges which, if left without attention, can cause drawbacks and unexpected financial impacts.

3.4 Company Strategic Landscape

As discussed in chapter 2, product development is not done in isolation, but in relation to the business environment of the company. As with generic product development, there are multiple ways of modularisation and modular product development, and there is no one way that is universally accepted as the “right way”. One tool, which provides support for modularisation by linking requirements from business environment to product structure is called Company Strategic Landscape (CSL). CSL is a framework model introduced by Juuti et al. (2007) that “defines the elements related to the product development operations and the production of the company” (Lehtonen 2007). The CSL-framework suggests that modular product structuring is affected by multiple key issues in the company either directly or indirectly. These issues and relations between them are shown in the figure below.

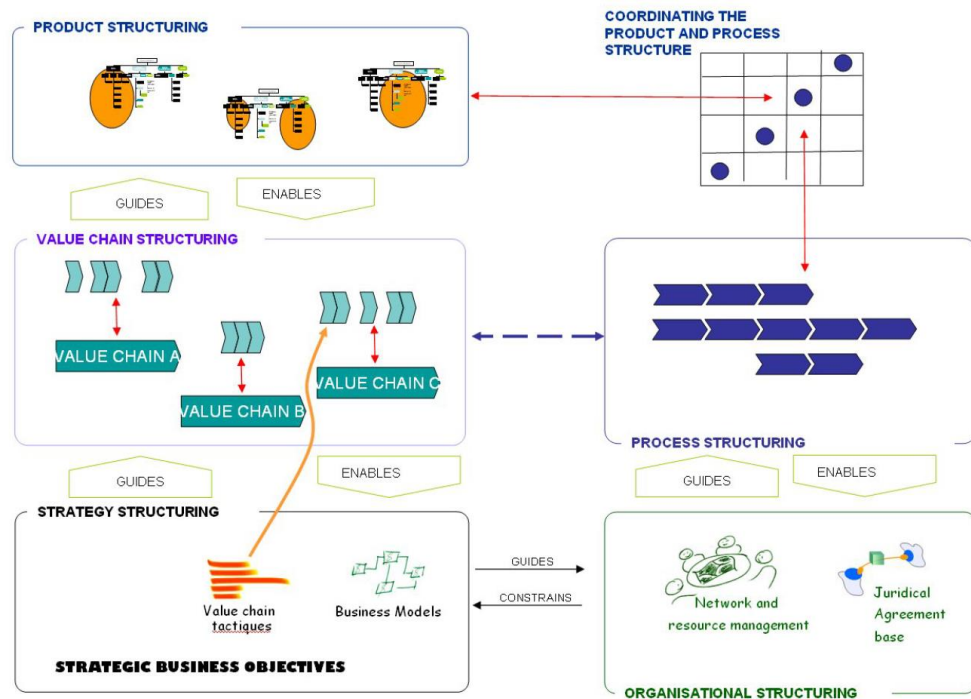


Figure 12. Company strategic landscape framework presents the topics from company business environment and relations between them. Figure from Lehtonen (2007).

Company structuring domains guide, enable and constrain each other as shown in the above figure. The key idea from CSL-framework is that product structuring and delivery process should not be viewed as separate entities, but as a synchronized entirety. For example, product structuring is guided by value chains, which in turn are both enabled and limited by product structure. Value chains are created according to company strategy structuring (the business goals). (Lehtonen 2007).

Lehtonen (2007) has presented multiple business cases in which the CSL-framework was used to guide the product structure design. For example, one of the cases was shifting the

production of an ambulance from one-off production to serial production. The framework model identified and presented key strategic goals to pursue to achieve the wanted product structuring. The presented cases demonstrate how CSL can be applied to real world product development projects.

3.5 The Brownfield Process

The Brownfield Process is a comprehensive approach to modular product design first introduced in Lehtonen et al. (2011), and further refined by the aforementioned publication's co-author J. Pakkanen (2015) in their dissertation. Pakkanen (2015) presents the process model in "more manageable sections" and with new steps that were not previously discussed. Pakkanen (2015) states that other previously published design supports are only partially applicable to "rationalising the existing product variety of a company towards a modular product family", and thus the Brownfield Process was selected for this thesis.

The Brownfield Process includes ten steps, which are shown in Figure 13. Each step of the BfP defines design information related to one of the Module System: partitioning logic, set of modules, interfaces, architecture and configuration knowledge. The process considers both business issues and design viewpoint, and aims to create a product family with modular architecture that fits into the company's business environment. Sales-delivery process and future updates of the product family are also taken into account with documentation of configuration knowledge in the process. The presented order of proceeding step-by-step from step 1 to 10 is based on the central business case in Pakkanen's dissertation, but other variations are also possible. The nature of the process is not strictly linear, and some iteration is present inherently. (Pakkanen 2015)

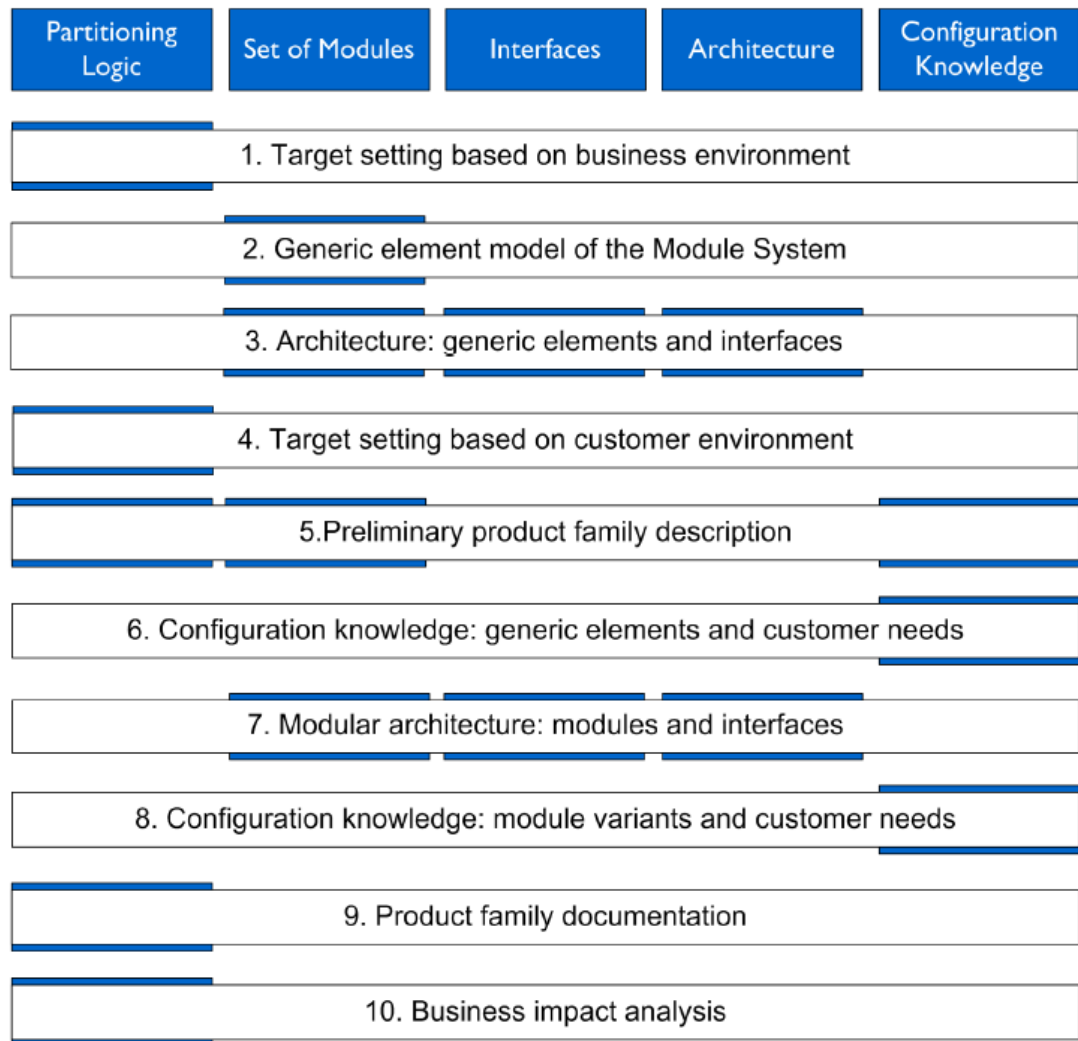


Figure 13. *The Brownfield Process steps and Module System (Pakkanen 2015).*

3.5.1 Step 1: Target setting based on business environment

The aim of the first step of the BfP is to define objectives for the modularisation process from a business point of view. The first task of the step is to select products for the modularisation process. It is suggested that if a wide assortment of products is present in the company, the product scope might need to be narrowed in order to reduce the complexity of the process. Narrowing the scope comes with benefits and drawbacks, as it is possibly less complicated to find configurable product elements and interfaces from a limited number of products, but on the other hand the results may only be limited to be applicable locally. (Pakkanen 2015)

The other task of the first step is the clarification of targets, for which the BfP proposes two approaches: cause-and-effect diagram from Juuti (2008) and Company Strategic Landscape (CSL) framework discussed e.g. by Lehtonen (2007). (Pakkanen 2015). The CSL framework was introduced previously in the chapter **3.4 Company Strategic Landscape**.

Pakkanen (2015) suggests cause-and-effect diagram to be used when there is a consensus within the product development team about the objectives and sought-after benefits of the modularisation process. The CSL is suggested to be used when a more comprehensive target setting is required and the objectives for the product development team are unclear. (Pakkanen 2015)

3.5.2 Step 2: Generic element model of the Module System

During the second step of the BfP, a preliminary division of product modules is made in relation to the generic element model. Expert product knowledge of the products in the selected scope is required during the step. Generic elements are preliminary modules of the products, and they are determined by what entities the company considers their products to consist of, for example sub-systems, function carriers, assemblies or single parts. Generic elements can be divided to, for example, structural and functional elements, but other division principles can also be applied. (Pakkanen 2015)

The generic elements should have as few commonalities as possible between each other in order to reduce variation in the product family. Commonalities can be, for instance, features and their geometric properties (Siddique & Natarajan 2006). The so-called 100% rule can be used to assess the generic element model's correctness. The rule is applied by checking whether the complete product scope is represented by the generic element model, or is there something missing. The result of the second step is a tentative hierarchical list of elements for module division, which is revised later in the BfP. (Pakkanen 2015)

3.5.3 Step 3: Architecture: generic elements and interfaces

The third step of the BfP results in a preliminary architecture of the generic elements and the interfaces between them. To start defining the architecture, it is suggested to use a matrix tool for identifying the relations between generic modules. For example, the matrix tool Design Structure Matrix (Steward 1981) can be used for this purpose. The parts, assemblies and subsystems related to each generic element are suggested to be focused on. (Pakkanen 2015)

As the aim of the step is to produce a preliminary architecture, or a layout, displaying the positions and interfaces between generic elements, 3D CAD-drawings are suggested to not be used. The reasoning is that detailed, accurate CAD-drawings describing the structure are likely not available, and simpler models may depict the general element positioning more clearly. Such models can be drawn with traditional office software, and an example is shown in Figure 14. The produced model can be thought to be the starting point for designing the interfaces between generic elements, which will be designed in detail later in the BfP. (Pakkanen 2015)

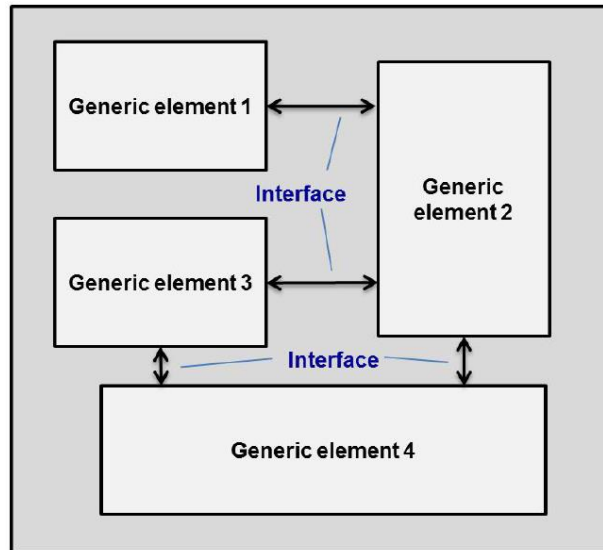


Figure 14. Example visualisation of generic elements layout and the interfaces between them. Figure originally from Fujimoto (2007), modified by Pakkanen (2015).

3.5.4 Step 4: Target setting based on customer environment

During the fourth step of the BfP, the need for variation in the modular product family from the customer's standpoint is established. As the BfP focuses on designing a modular product family from existing products, customer requirements for the product family can be formalized using previous sales experience, as products have been delivered to customers against some requirements. These formalized customer requirements are needed for configuration rules for the product family. Configuration rules determine what type of product is delivered when specific customer requirements are present. Requirements that cannot be described formally are suggested to be left out of the systematic configuration, leaving these requirements to be partly configurable. (Pakkanen 2015)

The BfP assumes that any basic requirements of the product are known throughout the company (e.g. a car must move), so these basic requirements are not focused on in the process. The current customer context should be analysed to ensure the customer requirements are up-to-date as they may have changed since the old products were delivered. To understand the need for product variation from customer standpoint, main customer questions should be defined. Main customer questions are questions that need to be asked to define a suitable product variant for a customer. The result of the fourth step is an overview of the customer processes where the products in the scope are used and how these processes and their options pose the need for product variability, and what are the questions that need to be answered to define a suitable product variant. (Pakkanen 2015)

3.5.5 Step 5: Preliminary product family description

The fifth step of the BfP defining the product family rationale is continued. The step focuses on identifying possibilities for added commonality and standardization of parts and assemblies. A preliminary product family structure is created as a result. (Pakkanen 2015)

The BfP suggests a modified product family master plan (PFMP) approach for preliminary definition of the product family. The approach suggests that when describing a product family, three views are included: customer view, generic elements and parts and assemblies. Relations between the views are identified and issues within the views defined. When analysing the relations, possibilities for standardization are attempted to be found. At least one generic element should link to each customer need. If a generic element has no relation to any of the listed customer needs, the generic element could potentially be standardized. It is possible to realise that multiple similar solutions have been used to solve the same customer need. In such cases, commonality between products could likely be increased. (Pakkanen 2015)

In addition to increased commonality and identified possibilities for standardization, the approach results in information that eases reducing the complexity of the generic elements. As the relations of generic elements parts and assemblies are mapped, duplications and redundancies could be identified, which should be avoided. (Pakkanen 2015)

3.5.6 Step 6: Configuration knowledge: generic elements and customer needs

During this step in the BfP, preliminary configuration knowledge is established. The configuration knowledge clarifies the relations between generic elements and customer needs related to variation. Documentation representing configuration knowledge in a clear manner will be useful later on, when possible updates, modifications or new versions of the product family are created. (Pakkanen 2015)

For mapping customer needs that cause a need for variation in relation to generic elements, a modified K-matrix approach is suggested. Generic elements are added on the rows and customer needs are listed on the columns of the matrix and their relations analysed. An example matrix is shown in Figure 15. The results of this step explain the relations between generic elements and customer needs and are used later in the BfP in definition of the product family architecture. The results can also be used to verify that a solution considers all the related customer needs. (Pakkanen 2015)

Modified K-Matrix (configuration knowledge matrix)

(1) Customer need requires generic element
 (2) Customer need excludes generic element
 (3) Customer need might affect generic element
 (empty cell) Customer need does not affect generic element

GENERIC ELEMENTS	CONTENT AND TYPE OF GENERIC ELEMENTS	CUSTOMER NEEDS	Customer need group 1	Customer need 1.1	Customer need 1.2	Customer need 1.3	Customer need group 2	Customer need 2.1	Customer need 2.2	Customer need group 3	Customer need 3.1	Customer need 3.2	Customer need 3.3	Customer need 3.4	Customer need 3.5	Customer need group 4	...
Generic element 1																	
Generic element 2										1							
Generic element 3			1				1										
Generic element 4							1										

Figure 15. Example of the modified K-matrix displaying relations between customer needs and generic elements. (Pakkanen 2015)

3.5.7 Step 7: Modular architecture: modules and interfaces

In the seventh step of the BfP, the architecture of the modular product family is further defined, including generic elements and their interfaces. Essentially, results of previous steps are combined and refined into a more detailed overview of the modular architecture. Generic elements types, their part sets and interfaces are focused on during this step. (Pakkanen 2015) The issues considered in this step are visualised in Figure 16.

Generic elements were first defined during Step 3, and the elements types are defined here. It is suggested that generic elements can be defined as one of the following three types: **standard, configurable or partly-configurable**. (Pakkanen 2015)

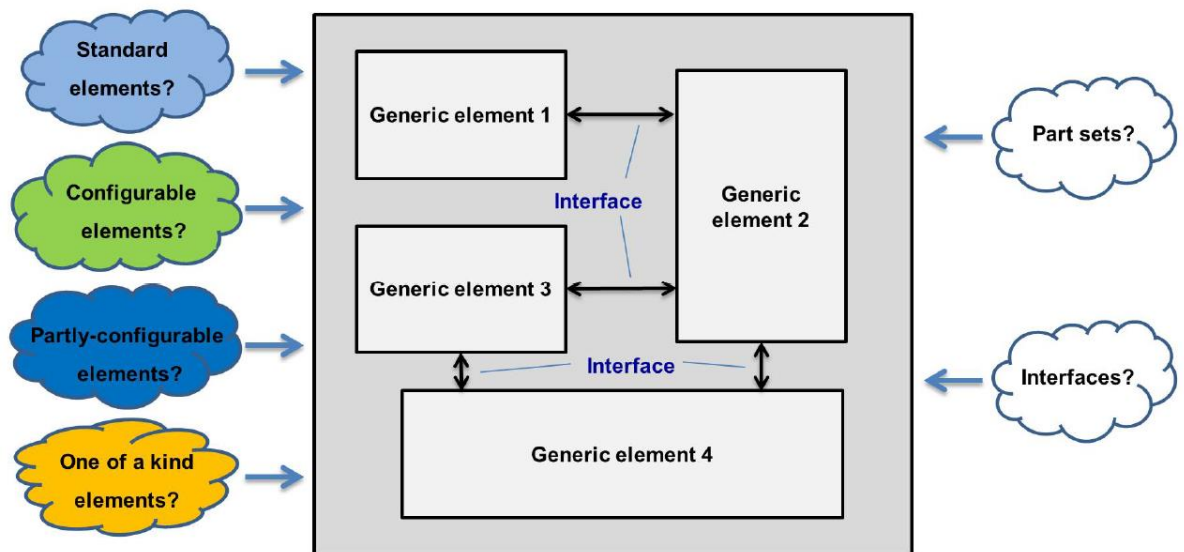


Figure 16. Generic elements, their part sets and interfaces are further defined in Step 7. (Pakkanen 2015)

If a generic element has no customer needs that pose a need for variation related to it, and one solution can be found for the element, it is a good candidate for a **standard element**. A **configurable element** has a related variation need from customer viewpoint, and a single solution is not applicable. In such case, a set of standardised, interchangeable modules are recommended to be considered. When it is not possible to define standardised modules, **partly-configurable elements** are often the result. These types of elements include both configurable standard sections and unique elements. (Pakkanen 2015)

In addition to identifying element types, their interfaces and part sets should be further defined. Preliminary configuration knowledge from Step 6 assists with analysing part sets. Part sets of a generic element are analysed by how well they meet the variation needs and assessing the similarity of their interfaces. Three common recognisable issues are suggested: existing part sets are justified, there are too many, or too few part sets. (Pakkanen 2015)

3.5.8 Step 8: Configuration knowledge: module variants and customer needs

The eighth step of the BfP includes defining configuration knowledge in relation to actual solutions defined in Step 7. In Step 6, configuration knowledge was defined in relation to customer needs and general elements. The results of this step explain the matches between specific customer needs and solutions. It is important to document the resulting configuration knowledge clearly, as it is useful during the sales-delivery process and the possible building of a configurator. (Pakkanen 2015)

It is suggested to use the same modified K-matrix that was used in Step 6. During this step, the content and type of each generic element is added to the matrix. Relations between each solution and customer needs are then analysed. The resulting matrix displays which customer needs require, exclude, might affect or do not affect a specific generic element or solution. Similarly, the compatibilities between generic element contents could be visualised with a V-matrix, named compatibility matrix in the BfP. (Pakkanen 2015) An example of a K-matrix with generic element contents and their types added is shown in Figure 17 and a compatibility matrix is shown in Figure 18.

The matrices are a simplified example for portraying the basic functionality of a configurator, and often a more advanced configurator software is used when a product has been developed to be easily configurable. This also applies to the configuration knowledge matrix discussed in step 6. (Pakkanen 2015)

Modified K-Matrix (configuration knowledge matrix)

(1) Customer need requires generic element / solution
 (2) Customer need excludes generic element / solution
 (3) Customer need might affect generic element / solution
 (empty cell) Customer need does not affect generic element / solution

GENERIC ELEMENTS	CONTENT AND TYPE OF GENERIC ELEMENTS	CUSTOMER NEEDS	Customer need group 1	Customer need 1.1	Customer need 1.2	Customer need 1.3	Customer need group 2	Customer need 2.1	Customer need 2.2	Customer need group 3	Customer need 3.1	Customer need 3.2	Customer need 3.3	Customer need 3.4	Customer need 3.5	Customer need group 4	...
Generic element 1	Solution "Alpha" (Standard element)																
Generic element 2	Solution "Beta" (Configurable element) Solution "Zeta" (Configurable element) Solution "Theta" (Configurable element)									1		1	1	1			
Generic element 3	Solution "Iota" (One of a kind element)		1				1									1	
Generic element 4	...			1	1	1		1	1								

Figure 17. Complete configuration matrix with generic elements, generic element contents (and types) and customer needs. (Pakkanen 2015)

Modified V-Matrix (compatibility matrix)

(1) Solution requires another solution
 (2) Solution excludes another solution
 (3) Solution might affect another solution
 (empty cell) Solution pairs do not have relations

GENERIC ELEMENTS	CONTENT AND TYPE OF GENERIC ELEMENTS	Generic element 1	Solution "Alpha" (Standard element)	Generic element 2	Solution "Beta" (Configurable element) Solution "Zeta" (Configurable element) Solution "Theta" (Configurable element)	Generic element 3	Solution "Iota" (One of a kind element)	Generic element 4	...
Generic element 1	Solution "Alpha" (Standard element)								
Generic element 2	Solution "Beta" (Configurable element) Solution "Zeta" (Configurable element) Solution "Theta" (Configurable element)								
Generic element 3	Solution "Iota" (One of a kind element)								
Generic element 4	...								

Figure 18. Example compatibility matrix for generic elements and their contents (Pakkanen 2015).

3.5.9 Step 9: Product family documentation

The previous steps in the BfP result in documentation if suggested approaches are followed, but this specified documentation step produces separate documentation. The resulting documentation includes product family description from design reasoning chain viewpoint. In the documentation, the contents of the product family and the customer needs and their corresponding elements and solutions are described. This documentation can be used as support material for sales and marketing and in re-design situations. (Pakkanen 2015)

A suggested approach for the documentation is Product Structuring Blue Print (PSBP), which aims at visualising the “partitioning logic and design reasoning aspects of the product family”. An example of a PSBP documentation is presented in Figure 19. In the PSBP approach, each generic element of the product family and their solutions, with colour-coded solution principles, are listed. The relations between variation needs from customer perspective and corresponding solution are also visualised. (Pakkanen 2015)

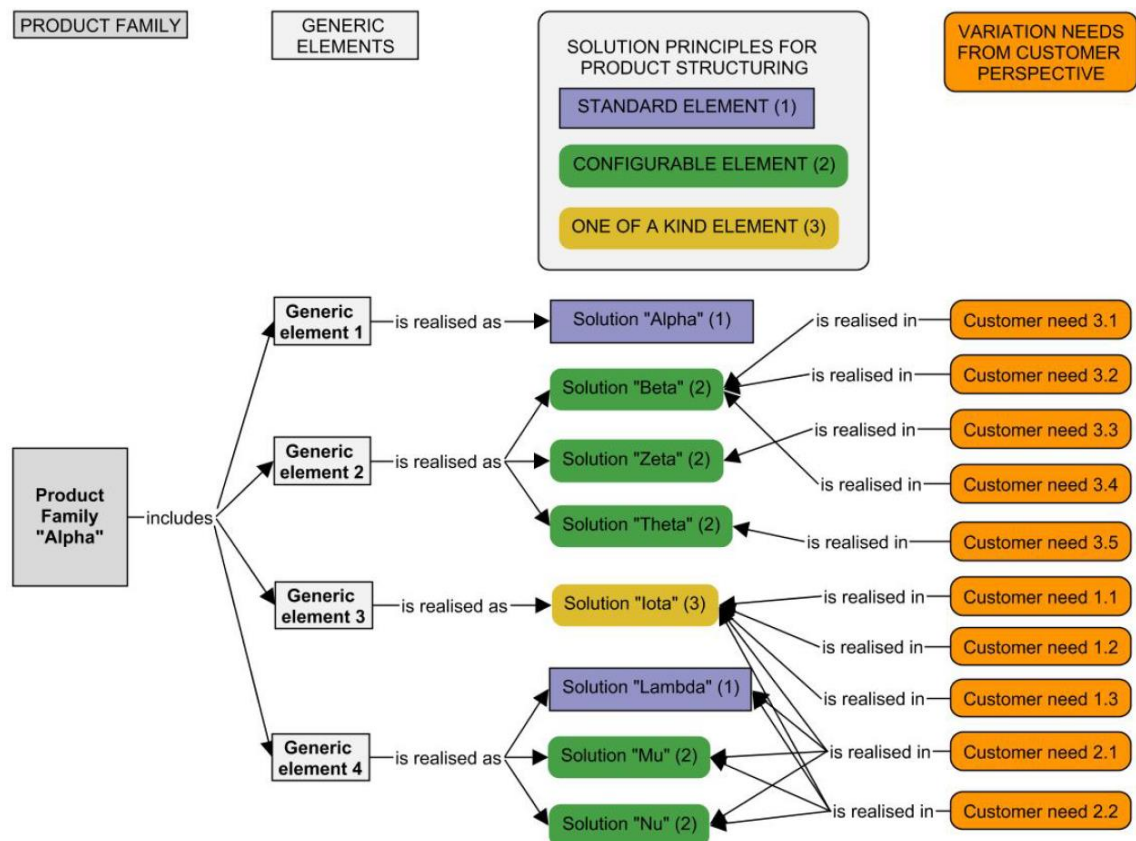


Figure 19. The PSBP documentation visualises the partitioning logic and design reasoning aspects of the product family. (Pakkanen 2015)

3.5.10 Step 10: Business impact analysis

During the tenth step of the BfP, business impact analysis is done. Analysing the business impact of the BfP is a way of assessing how the process has performed and if the developed modular product family is competitive. The BfP suggests a comprehensive analysis model for analysing the business impact of the modular product family. The results of the analysis provide information for, for example, making the decision if the product family is a go or a no-go. (Pakkanen 2015)

The business impact analysis of the BfP is not described in detail here. An overview of the suggested analysis model is presented in Figure 20. The analysis method considers all five elements of the Module System and the guiding principles and mechanisms related to them. The possible cost, income, quality, resource and time effects in money of these principles and mechanisms are estimated. (Pakkanen 2015) A detailed description of the business impact analysis can be studied from the original source, Pakkanen (2015).

The “guiding principles in modular product family development aiming for configurable products” in Figure 20 are essentially the value creation mechanisms displayed in Figure 11. Based on these value creation mechanisms, more detailed analysis tools for analysing the business impact can be developed. Each VCMs business impact can be assessed by, for example, roughly estimating how much money would be saved (or lost) if development project was successful and 50 new modular products would be delivered in a year compared to old design. (Pakkanen 2018)

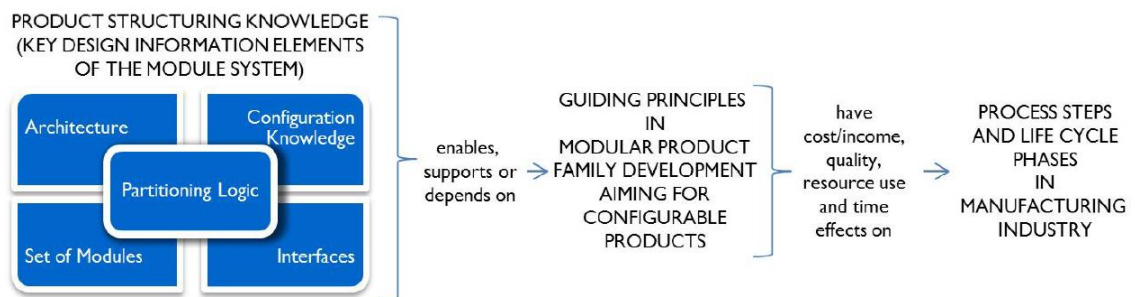


Figure 20. Overview of the business impact analysis model in the BfP (Pakkanen 2015).

4. BUSINESS CASE

The findings in literature were utilized in forming a product development proposal in a company in the aggregate business. The products to be developed were rock crushing stations, which are introduced in this chapter. A project that was to produce a development proposal for the crushing stations was launched in the company, and the project and the proposal are introduced here.

4.1 Rock-crushing stations

Crushed rock is one of the main ingredients in asphalt and concrete and thus used in construction of highways, bridges and buildings. Rock can be crushed with a wide range of crushers which crush the rock in different ways, making it smaller and shaping it. As rock is available around the world, rock crushers are deployed in various ways. One rock crushing solution is called “crushing station”, in which a rock crusher is mounted on a stationary, solid support structure. Examples of crushing stations are displayed below in Figure 21.



Figure 21. *Rock crushing stations from Sandvik, an unknown manufacturer and Terex.*

Often rock crushing is done in stages to achieve the wanted size and shape, and rock is moved from station to station with conveyors and hoppers. An entirety consisting of crushers, hoppers, conveyors and screening equipment is called a plant. Stationary crushing plant is often deployed when crushing can be done in the same place for a considerable period of time and a mobile application is thus not required.

4.2 Project description

The case company had various designs for crushing stations with same crushers, essentially fulfilling the same customer needs. The designs were developed in three different locations without a connection between the engineering teams. One of the three locations produced some documentation to support the designs, such as product brochures listing technical specifications and options alongside pre-defined layouts for plants, which was suitable material for sales support. Other location had produced no such documentation, and third location had mainly engineered designs for engineered-to-order (ETO) projects, so level of sales support documentation was naturally low.

The market for crushing stations was projected to grow and existing designs were hindering the competitiveness of the company. The designs were generally difficult to erect on customer site and transportation was troublesome. Engineering issues were also present as structures had failed on customer site and some operational and maintenance activities were difficult to carry out due to the design. To answer to the potential increased business opportunities in the market, the crushing stations needed to be improved. A similar project increasing the quality of another product family was previously performed in the company and based on feedback from market areas, the customers wanted crushing stations to have the same level of increased quality.

Initially, the goal of the project was to conduct a pre-study and generate a product development proposal for a globally manufacturable design. The scope of the project was later amended to produce a product development proposal for one of the existing designs and to identify the differences between the existing designs. The pre-study consisted of data collection of the existing designs from different sources, evaluation of the existing concepts and identifying the key drawbacks that should be improved.

4.3 Evaluation of concepts

After collecting the data of the existing designs, which included 3-dimensional computer-aided design (3D CAD)-models, drawings and other documentation, a list of evaluation criteria was produced. The evaluation criteria (Figure 22) were derived from customer requirements and key targets for the company. Generic requirement lists by Pahl et al. (2007) and Ulrich & Eppinger (2012) were also utilized. The list consisted of nearly a hundred criteria which were formatted and weighted in levels, as suggested by Pahl's et al. (2007) evaluation process. In order to determine the evaluation criteria's validity, the list was compared with the rules suggested by Pahl et al. (2007):

- No relation between criteria allowed
- Each criterion must be measurable or at least describable verbally
- Criteria must be defined so higher score indicates "better"
- Criteria list takes all relevant requirements and constraints into account

LEVEL	EVALUATION CRITERIA
1	STRUCTURE
2	How well the structure can handle loads?
2	How well the structure resists external effects?
2	How well the structure resists fatigue?
2	How well the structure supports customization? (i.e. adding platforms)
1	SPATIAL REQUIREMENTS
2	How compact is the structure on site, assembled?
2	How simple is the structure? (high score = simple)
1	WEIGHT / MASS
2	How light is the total structure? Low score = heavy
1	MAINTENANCE
2	How easily are maintenance points accessible?
2	How well the maintenance platforms support maintenance operations?
1	OPERATION
2	How well the structure supports operation activities?
1	MANUFACTURING
2	How well is the structure globally manufacturable?
2	How well are materials globally available?
2	Surface treatment / corrosion prevention quality
2	Current supply chain / supplier base
1	TRANSPORTABILITY / PACKING
2	How well the structure can be transported containerised?
2	How well the structure can be transported on road?
1	LAWS & REGULATIONS
2	CE-marking
1	QUALITY
2	How good is the quality documentation level?
2	How good is the engineering documentation level?
1	PRICE
2	How low is the manufacturing cost? Low score = expensive
2	How low is the transportation cost? Low score = expensive
2	Site installation cost
2	Foundations cost (foundations, boltings etc.)
1	SAFETY
2	How well the structure supports safe maintenance?
2	How well the structure supports safe operations?
2	How unlikely is it to misuse the plant?
1	SITE INSTALLATION
2	How complex is the site installation process?
2	How much time does the site installation require?

Figure 22. Evaluation criteria for the selected designs. First two levels of three are shown. Criteria weights are not displayed.

The evaluation revealed that the existing products had deficiencies hindering their business potential. The products weren't utilizing the company's manufacturing and sales processes, and a high level of manual work was included in each product delivery. Additionally, it was found that the designs had flaws hindering the delivery process and a lack of features that would improve their transportability and site installation. Overall, the existing concepts were deemed outdated and the technical solutions lacking.

4.4 Product development proposal

The product development proposal was created based on feedback from different parties inside and outside the company, business analysis and the evaluation of concepts. It was identified that product development would be required to increase sales and profitability of the products. Key findings were that the products were not utilizing company manufacturing and sales processes, which increased the manual work in each delivery and reduced the potential delivery capacity, resulting in lost sales opportunities. Additionally, the design of the crushing stations when compared to other crushing product families in the company's portfolio was outdated and lower quality. Furthermore, competition comparison revealed that competing companies were offering products that were responding better to customer needs and included features that increased the products' profitability.

The proposed actions were summarised as a suggestion to *“develop the crushing stations to a product family with configurable products and standard manufacturing & sales processes to increase the business”*. Four proposed main actions to be taken were:

1. Manufacturing, transportation, on-site erection to be made simpler, faster
2. Incorporate company manufacturing and sales processes
3. Create quality documentation to support installation, sales, third parties
4. Update design

These actions were further expanded with early suggestions for concrete actions and tasks that would be required to complete to achieve these main goals. As stated in the summarised proposal, the development of the product family was suggested to be towards configurable products. The concrete action suggested was to increase the modularity of the products with an existing product family, which was found to have multiple similarities and possibilities for commonality with the crushing stations.

At the time of writing the product development proposal was still in draft-phase and required some further work, but the main idea and goals were beginning to clarify. It was yet unclear whether the proposal would be launched into a product development process, but initial feedback within the company was positive. Initial technical specifications, concept drafts and basic visualizations were started as support material for the proposal and as preparation for the possible development.

5. CONCLUSIONS AND DISCUSSION

Generic engineering design processes are controlled processes that help product development projects to reach the best result most cost-efficiently, fastest and most competitively. One of the critical steps in design processes is conceptual design, which includes the creation, evaluation and selection of concepts. The selected concept or concepts will be developed into products, so it is important to ensure the concept's strength from financial, strategical and technical points of view. There are various ways for evaluating concepts, but systematic methods are the most efficient. These methods can be either qualitative or quantitative. In the author's opinion it is worthwhile to use more than one method or a combination of methods to ensure the best concept is selected.

One of the drivers for product development is to answer to customer needs. A challenge for any company that develops products is developing products that can answer to changing customer needs. A design methodology that is utilized in solving the challenge is modularisation. With modularisation, companies can offer an increased product variety from the customers viewpoint while reducing the complexity of their own processes. Modularity can be defined in different ways, but two central concepts are interchangeability and commonality. Module systems with interchangeable modules enable different product configurations, increasing product variety. Commonality in products can enable streamlining and reducing the costs of manufacturing processes. In addition to benefits, modularisation introduces challenges which can have a negative impact on the company operations if they are not considered.

Developing a modular product family from existing products in a company introduces challenges that can be difficult to identify. Brownfield Process is a design support designed specifically for such cases. With Brownfield Process a company can find ways to reduce the complexity of their operations and increase the profitability of their products, even if the goal is not to develop a fully modular product family.

The business case discussed in this thesis is introduced as an overview and it may seem to be a separate section with little relation to the discussed theory. However, the literature review has enabled the author to understand the various aspects that need to be considered in product development and provided multiple tools that have been utilized during the project. For example, some of the concept evaluation tools introduced in the literary review section of this thesis were directly used in the project. The business case is described vaguely to protect the business and the company's intellectual property. Overall, the author is pleased with the early results and how the literature review supported the project.

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